Observations of Neutral Atoms from the Solar Wind

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Abstract. We report observations of neutral atoms from the solar wind in the Earth's vicinity with the Low Energy Neutral Atom (LENA) imager on the IMAGE spacecraft. This instrument was designed to be capable of looking at and in the direction of the Sun. Enhancements in the hydrogen count rate in the solar direction are not correlated with either solar ultraviolet emission or suprathermal ions and are deduced to be due to neutral particles from the solar wind. The energy of these neutral particles is inferred to exceed ~1 keV, consistent with solar wind energies. This is based on the observation of oxygen ions, sputtered from the conversion surface, observed in the time-of-flight (tof) spectra. In addition, the sputtered oxygen abundance tracks the solar wind speed, even when IMAGE is deep inside the magnetosphere. These results show that low energy neutral atom imaging provides the capability to directly monitor the solar wind and/or magnetosheath from inside the magnetosphere.

1. Introduction

The Low Energy Neutral Atom (LENA) imager is one of six science experiments that were launched on the IMAGE observatory on March 25, 2000. This instrument was designed to accomplish remote sensing of the neutral component of space plasmas at energies from a few tens to a few thousands of electron volts [*Moore et al.,* 2000]. Neutral particles in this energy range, which encompasses most of the plasma in the heliosphere, have not previously been systematically observed. Similar to instruments which image more energetic neutral atoms, LENA has the ability to not only detect the neutral atoms, but also determine their mass, energy and direction (polar and azimuthal angles) [*Hsieh et al.,* 1992]. LENA was designed to observe the sun directly and responds to neutrals of energies of the order of 1 keV. Consequently, the instrument is capable of observing the fraction of the solar wind flow that is neutral hydrogen, which has been long-recognized as of potentially great importance for understanding solar, interplanetary and magnetospheric physics [*Akasofu,* 1964; *Wurz et al.,* 1995].

Charge exchange between solar wind protons and neutral particles can be primarily responsible for the formation of a neutral solar wind, although there is also a neutral component due to recombination of solar wind ions with solar wind electrons [*Gruntman,* 1994]. These charge-exchanging neutrals may be interstellar neutral atoms, originate from dust grains [*Holzer,* 1977; *Schwadron et al.,* 2000] or be part of the Earth's geocorona. The potential importance of charge exchange with the Earth's exosphere is highlighted by the fact that the geocoronal density at the magnetopause is comparable to that of the solar wind [*Rairden et al.,* 1986]. Since charge exchange with the geocorona will occur preferentially near the Earth, the neutral solar wind characteristics may be heavily influenced by magnetospheric structures and activity. This can lead to wider angular profiles with signals coming from directions offset from what might be expected from solar wind charge exchange upstream of the Earth's bowshock. In addition, if the Earth is in conjunction with Venus, LENA might observe an increased neutral solar wind flux due to charge exchange in the atmosphere of Venus.

2. Observations from the June 8, 2000 Event

About one month after beginning science operations on May 5, 2000, LENA had an opportunity to observe a coronal mass ejection (CME) and its effect on the terrestrial environment (see companion papers in this issue by Moore *et al.* [2000b] and Fuselier *et al.* [2000]). On June 6, 2000, an intense solar flare was observed and was followed by a full-halo CME propagating toward the Earth. The shock wave driven by this CME was observed by the Advanced Composition Explorer (ACE) and the Solar and Heliospheric Observatory (SOHO) spacecraft at about 08:42 UT on June 8, 2000 at the L1 point, 235 R_E upstream from the Earth, and by the Wind spacecraft, 41 R_E upstream, at about 09:05 UT. At 09:11 UT this disturbance passed the Earth where it and its effects were observed by the IMAGE spacecraft.

Figure 1 shows a LENA spectrogram of the combined hydrogen and oxygen count rate as a function of time on June 8, 2000, the day the CME-driven shock passed the Earth. Also see the first two panels of Figure 4 of Moore *et al.* [2000b] for an image of the sun pulse brightening. The bright streak, in time, near 180° is a signal initially thought to represent a response to the EUV photon flux from the Sun. The angular range of the Earth is indicated by the dashed white lines, and the yellow brightening around 09:50 UT is the oxygen burst discussed by Fuselier *et al.* [2000]. However, when the sun signal increased significantly at the arrival of a shock (at 09:11 UT) in the solar wind associated with the CME, it was concluded that at least part of this signal must represent neutral atoms in the solar wind. Subsequent analysis based on in-flight and calibration data shows LENA to have a negligible response to UV at ambient pressures experienced on orbit (we expect the UV response to scale with pressure at or near the conversion surface).

As additional evidence that LENA is not responding to UV, Figure 2 shows the EUV data from SOHO [*Judge et al.,* 1998] on June 6-8, 2000. The upper solid line shows the photon flux between 0.1 and 50 nm and the lower dashed curve shows the photon flux between 24 and 34 nm. The activity on June 6 associated with the CME is apparent in the data with some subsequent activity on June 7 (which was not associated with a LENA count rate enhancement). During the event on June 8, indicated by the vertical line, there is no enhancement in the UV flux, indicating that the enhancement seen in the solar direction by LENA is not due to an increase in solar EUV.

UV radiation is not the cause of the observed enhancement from the solar direction. However, it is possible that this increase is due to suprathermal ions penetrating the collimator [*Moore et al.,* 2000a]. At the time of the June 8, 2000 event a potential of about 8.8 kV was across the collimator to filter out all ions with energies up to about 50 keV/e, while above about 100 keV/e most ions can traverse the collimator and arrive inside the instrument. The gap between the collimator plates varies from about 20 mm at the front to about 12 mm at the back so that the electric field varies from 444 to 730 kV/m over a distance of 93 mm. Because ion spectra at these energies in most space plasma environments follow rapidly decreasing power laws [*Collier et al.,* 1993], the primary contributor to the energetic ion flux entering LENA is likely close to 50 keV/e.

It is possible that the enhanced sun pulse seen in LENA observations could be due to ions with energies at or above 50 keV/e. If this is the case, such ions would have been observed by the Electron, Proton, and Alpha Monitor (EPAM) aboard the ACE spacecraft. The LENA background-adjusted counts per spin from the solar direction shown in Figure 3 have been compared with the ACE/EPAM ion flux data for this event. The LENA data peak shortly after the shock's passage and slowly decrease for about an hour thereafter. The ACE/EPAM flux data for ions with energies between 47 and 65 keV/e, which includes the 50 keV/e low energy limit for LENA ion admittance, show a step-function type increase of 25-50 at the time of the shock. If the LENA response were due to these energetic ions, we would expect the time profiles for the observations to be much more similar. This suggests that the enhanced sun signal observed by LENA is not due to these suprathermal ions.

The conclusion that the sun pulse enhancement is not due to suprathermal ions is also supported by observations by the Wind spacecraft and magnetopause modeling. Fig. 3 shows the solar wind ram pressure observed by the Wind spacecraft (with dashed lines on the right hand y-axis). The times when the high latitude magnetopause model of Boardsen *et al.* [2000] predicted that IMAGE was inside the magnetosphere are indicated by the black bars on the top x-axis. The Wind spacecraft at this time was about 41 R_E upstream and about 27 R_E off the Sun-Earth line in the minus y GSE direction, well within the $\sim$40 R_E scale length inferred by Collier *et al.* [1998] for IMF correlations, making it likely that Wind was a reliable interplanetary monitor. Although the Boardsen *et al.* model predicts that IMAGE moved across the magnetopause eight times in this three hour period, there are no sudden jumps in the LENA count rate associated with these crossings as would be expected in ion data at energies around 80 keV [*Paschalidis et al.,* 1994]. Furthermore, when IMAGE is inside the magnetosphere, we would not expect the energetic ions to arrive from a narrow range of directions as the "sun pulse" does. In short, the observed enhancement cannot be explained by energetic ions either inside of or outside of the magnetosphere.

We conclude LENA observed neutral particles from the solar direction during this event, indicating the sun pulse was and probably in general is primarily due to neutral particles. We now address the issue of whether or not the neutral atom energies are consistent with solar wind-like energies of the order of 1-5 keV. Figure 4 shows LENA calibration data taken at the University of Denver neutral beam facility [*Stephen et al.,* 1996]. The upper panel shows a time-of-flight spectrum resulting from incident 30 eV atomic hydrogen. There is a well-defined hydrogen peak at low times-of-flight with no evidence of an oxygen peak. An oxygen peak appears when the energy of the incident neutral hydrogen exceeds 300 eV. Above this transition, as shown in the lower panel of Fig. 4 for 1000 eV atomic hydrogen, a significant oxygen peak is present, believed to be due to the sputtering of adsorbed oxygen or water from the conversion surface.

Figure 5 shows a time-of-flight spectrum taken during the enhancement on June 8, 2000. The spectrum only includes events coming from the general direction of the Sun. Note the prominent oxygen peak. Since large neutral oxygen fluxes do not occur in the solar wind, this suggests the neutral hydrogen has energy $\sim$1 keV, above which sputtering can occur. In addition to the hydrogen and oxygen peaks, there is a third peak which appears in the in-flight data but was not observed in the calibration data. This may be due to data artifacts because in-flight the instrument is running at a higher start microchannel plate bias level.

There is a relatively larger oxygen signal in Fig. 5, the in-flight data, as compared to Fig. 4, the calibration data. Because LENA was only calibrated to 1 keV, we cannot make any quantitative statements about the energies of the neutral hydrogen except that they are comparable to or greater than 1 keV. It is possible that the ratio of sputtered oxygen to detected hydrogen is a very sensitive function of energy, which might explain the larger relative abundance of oxygen to hydrogen in the in-flight data. In addition, it is possible that at higher energies part of the hydrogen peak is also of sputtered origin.

The ratio of hydrogen to oxygen in the LENA time-of-flight spectrum may be used to monitor solar wind speed from inside the magnetosphere. The left hand y-axis and solid line in Figure 6 show, as a function of time, the solar wind speed as observed by the SWE instrument on Wind. The right hand y-axis and solid circles indicate the background-adjusted integrated hydrogen to oxygen count ratio in the sun sector from hourly averaged tof spectra. Prior to the shock passage, the ratio is 0.29 ± 0.01 while after the shock passage the ratio is 0.46 ± 0.05 indicating that LENA has observed the solar wind speed increase from inside the magnetosphere.

3. Discussion

LENA has observed a neutral particle component in the solar wind. These observations can be used to estimate the neutral flux during the enhancement period. These estimates will be compared to expectations. As shown in Fig. 3, the count rate during the enhancement is about 15 counts per spin. Since each spin sector is observed for about 2.7 seconds, this reduces to a count rate of 5.6 s^{-1}. At solar wind energies, LENA's neutral hydrogen detection efficiency was measured to be about 6.4×10^{-5}. We regard this as being correct to within a factor of two, considering the different conditions in flight and the scatter of the data in the efficiency curves. LENA's entrance aperture has an area of 1 cm^2, which yields a flux of about 8.8×10^4 $cm^{-2}s^{-1}$. At that time, the solar wind flux was $\sim 10^9$ $cm^{-2}s^{-1}$ (12 cm^{-3} density and 800 km/s speed) yielding a flux ratio of neutrals to solar wind protons of about 10^{-4}.

This value is comparable to the expected neutral solar wind component at 1 AU [*Holzer,* 1977; *Gruntman,* 1994]. However, the LENA observations include a potentially significant contribution due to charge exchange with neutral hydrogen in the geocorona. On the other hand, given the IMAGE orbit on June 8, 2000, the neutral solar wind impinges on LENA close to the edge of its field-of-view and so may be incompletely observed.

To illustrate the potential importance of charge exchange with the Earth's geocorona, we will show a simple estimate of the expected fraction of the flux signal resulting from this effect. The hydrogen atom distribution in the geocorona is a smoothly varying function of the distance from the center of the planet. Using the geocoronal density N(R) determined by Wallace *et al.* [1970] as

$$\mathrm{N(R)} = 10 \cdot \left(\frac{11}{\mathrm{R}}\right)^3 \mathrm{cm}^{-3}, \tag{1}$$

where R is the distance from the Earth in Earth radii, we can calculate the neutral atom flux due to charge exchange with the geocorona, F_{cex}. The range of Wallace *et al.'s* data is about 3-15 R_E. Following the work of Roelof [1997] and Roelof and Skinner [2000] we write

$$\mathrm{F_{cex}} = \int_{\mathrm{r_{mp}}}^{\infty} \mathrm{N(R)}\, \sigma\, \mathrm{n_{sw} v_{sw}}\, \mathrm{dR}, \tag{2}$$

where r_{mp} is the distance of the magnetopause from the Earth.

The solar wind neutrals are expected to emerge from the charge exchange collision with their initial velocity, v_{sw}, and the solar wind density, n_{sw}, will not be significantly depleted. Thus, the fraction of the solar wind density we expect to be neutral due to its interaction with the Earth's geocorona is simply

$$\frac{n_{cex}}{n_{sw}} = \int_{r_{mp}}^{\infty} N(R)\,\sigma\,dR, \tag{3}$$

Using equation (1) for the neutral density and taking $\sigma \sim 1.6\text{x}10^{-15}$ cm^2 [*Gealy and Van Zyl,* 1987], we get

$$\begin{aligned} \frac{n_{cex}}{n_{sw}} &= 10\,\mathrm{cm}^{-3} \cdot 11^3 \cdot 1.6\text{x}10^{-15}\,\mathrm{cm}^2 \cdot 6371\text{x}10^5\,\mathrm{cm} \cdot \int_{r_{mp}}^{\infty} \frac{dR}{R^3} \\ &= \frac{6.8\text{x}10^{-3}}{r_{mp}^2}, \end{aligned} \tag{4}$$

where r_{mp} is measured in Earth radii.

At standard magnetopause distances of 10 R_E, this results in a fraction of about 10^{-4}, comparable to the expected neutral solar wind component at 1 AU [*Holzer,* 1977; *Gruntman,* 1994] so that this effect under normal circumstances will tend to double the neutral solar wind flux.

4. Conclusions

We have reported observations of a count rate increase observed by the LENA imager on June 8, 2000 when a shock driven by a CME associated with a solar flare on June 6, 2000 arrived at the Earth. By establishing that the signal coming from the general direction of the sun is not due to UV photons or suprathermal particles, we have concluded that the enhancement (and likely the pre- and post-event signals) is due to neutrals in the solar wind. We have shown based on a comparison between LENA time-of-flight spectra from calibration and from this event that the observed neutral hydrogen energies are $\sim$1 keV, energies characteristic of the solar wind. In addition, we observed in the solar wind neutral particle signals a large solar wind velocity jump associated with the shock passage. We estimate, based on LENA efficiencies from calibration data and the observed neutral solar wind flux, a solar wind neutral flux to solar wind ion flux ratio of about 10^{-4}. This is consistent with predicted neutral solar wind fluxes at 1 AU. However, we point out that much of this signal may be due to solar wind charge exchange with the geocorona near the magnetopause. These results show that low energy neutral atom imaging may provide the capability to directly monitor the solar wind and/or magnetosheath from inside the magnetosphere.

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Figure Captions

Figure 1. A LENA spectrogram showing the combined hydrogen and oxygen count rate as a function of time on June 8, 2000. The y-axis shows the spacecraft spin angle. The direction and angular range of the Earth is indicated by the white dashed lines. The "sun pulse" is the streak hovering around 180°. This signal increases by about a factor of two when the shock passes at 09:11 UT.

Figure 2. EUV data showing photon flux from SOHO on June 6-8, 2000. The upper solid line is the photon flux from 0.1-50 nm and the lower dashed curve shows the photon flux from 24-34 nm. The flares on June 6 and 7 are apparent in the data. However, there is no enhancement during the event on June 8, showing that LENA is not responding to UV light at this time.

Figure 3. A comparison between the LENA sun sector count rate data and the solar wind ram pressure on June 8, 2000. This figure also shows with black bars along the upper x-axis when the IMAGE spacecraft based on the high-latitude magnetopause model of Boardsen *et al.* [2000] is inside the magnetosphere. The model predicts that during the June 8, 2000 event IMAGE moved back and forth across the magnetopause many times. This implies that if IMAGE were responding to energetic particles during this time, there would be changes in the signal corresponding to the boundary crossings. Because no such changes are observed and the distribution is less isotropic than would be expected from energetic particles, it is concluded that LENA is not responding to suprathermal ions during this time period. Both the solar wind ram pressure and the Boardsen *et al.* model results are derived from Wind spacecraft data.

Figure 4. The two panels in this figure show a comparison of the time-of-flight

spectra from the Denver University calibration resulting from incident atomic hydrogen. The top panel shows a time-of-flight spectrum resulting from 30 eV atomic hydrogen. Note the absence of a sputtered oxygen peak. The lower panel shows a time-of-flight spectrum resulting from 1 keV atomic hydrogen. At this higher, solar wind energy, a sputtered oxygen peak is apparent in the time-of-flight data.

Figure 5. This figure shows a LENA time-of-flight spectrum taken during the June 8, 2000 event from 0900-1100 UT. The spectrum only includes events coming from the general direction of the sun. The pronounced oxygen peak in the spectrum indicates that the neutral hydrogen energies are $\sim$1 keV, consistent with expected neutral solar wind energies.

Figure 6. The jump in solar wind speed observed by Wind during the shock passage on June 8, 2000, indicated by the solid line and left hand y-axis, is reflected in the ratio of atomic hydrogen to sputtered oxygen signal observed by LENA coming from the direction of the sun, indicated by the solid circles and right hand y-axis. The data in this figure are integrated counts from the sun direction over all spins during the one hour intervals. The hydrogen peak was taken to be channels 151-190 and the oxygen peak was taken to be channels 401-1000. A background rate was subtracted off both the hydrogen and oxygen peaks based on the number of counts appearing between channels 301-400, where no peak is expected. The count rates during this period are low enough so that the microchannel plates are not saturating. Because IMAGE is inside the magnetosphere during most of the time period covered by Fig. 6, these results indicate that low energy neutral atom imagers can directly monitor interplanetary conditions from inside the magnetosphere.

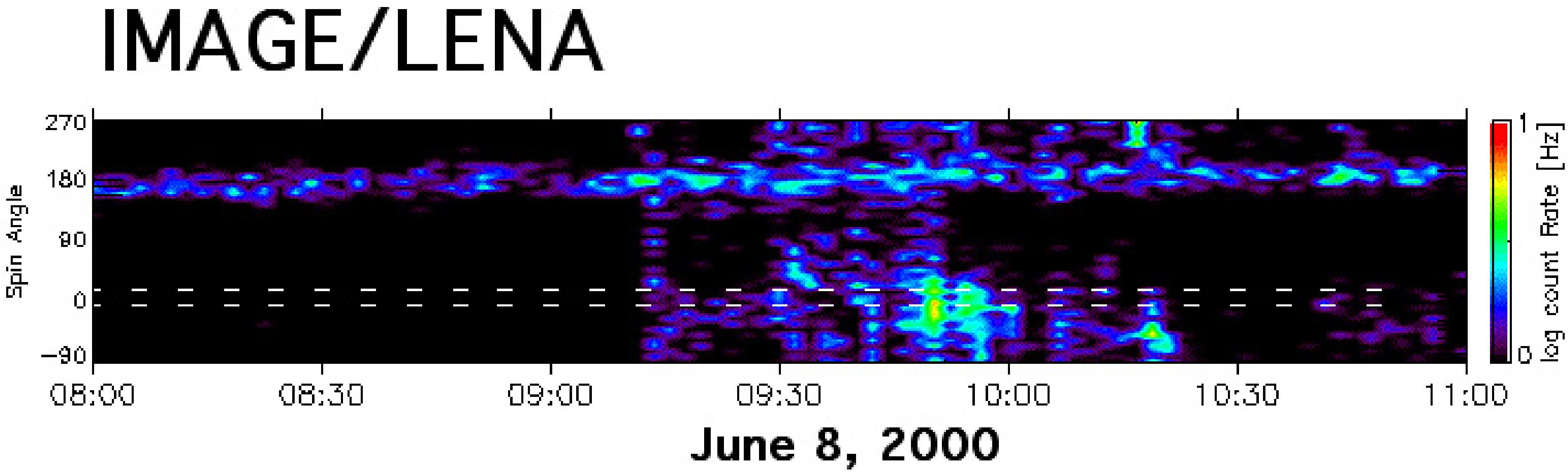
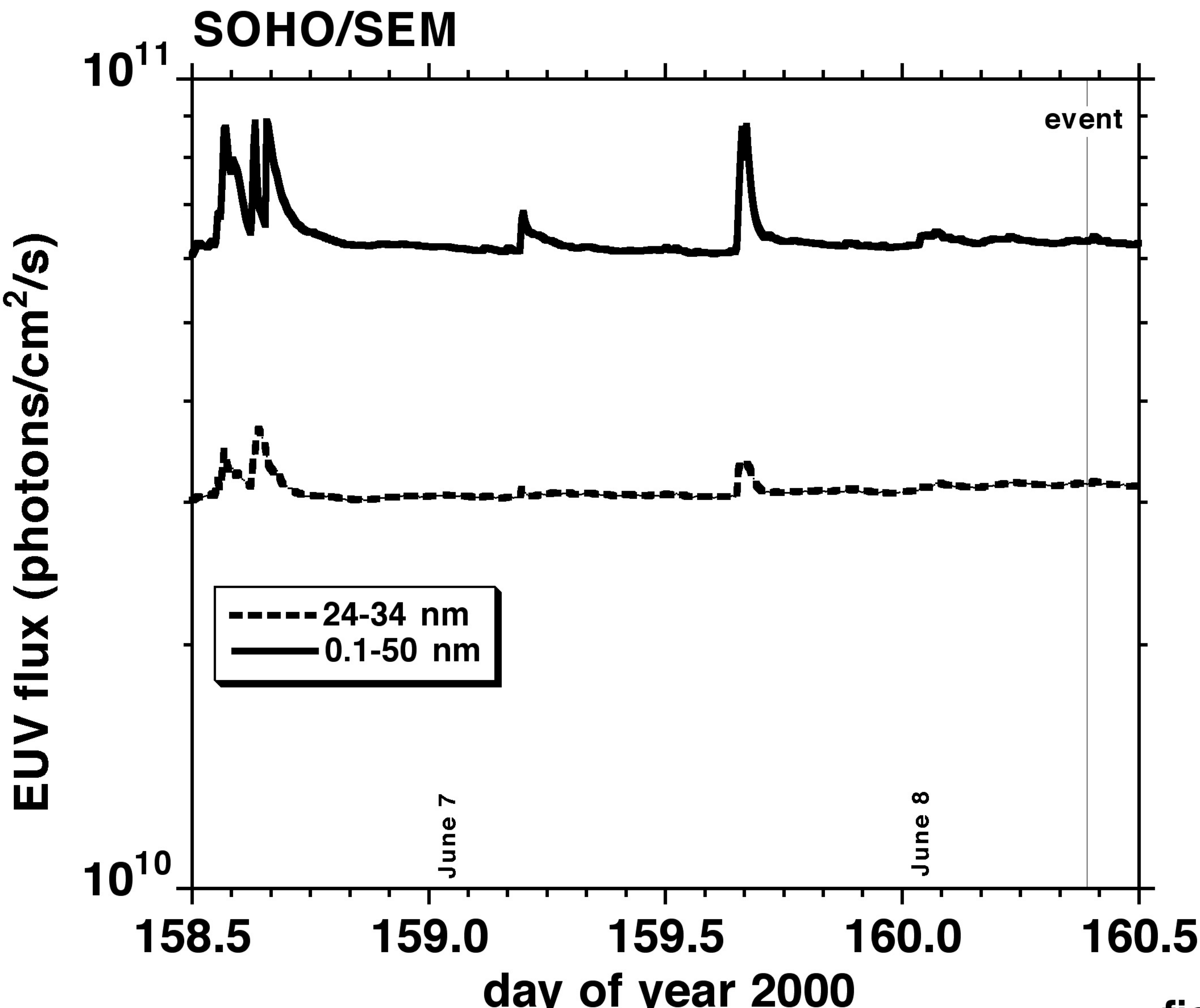
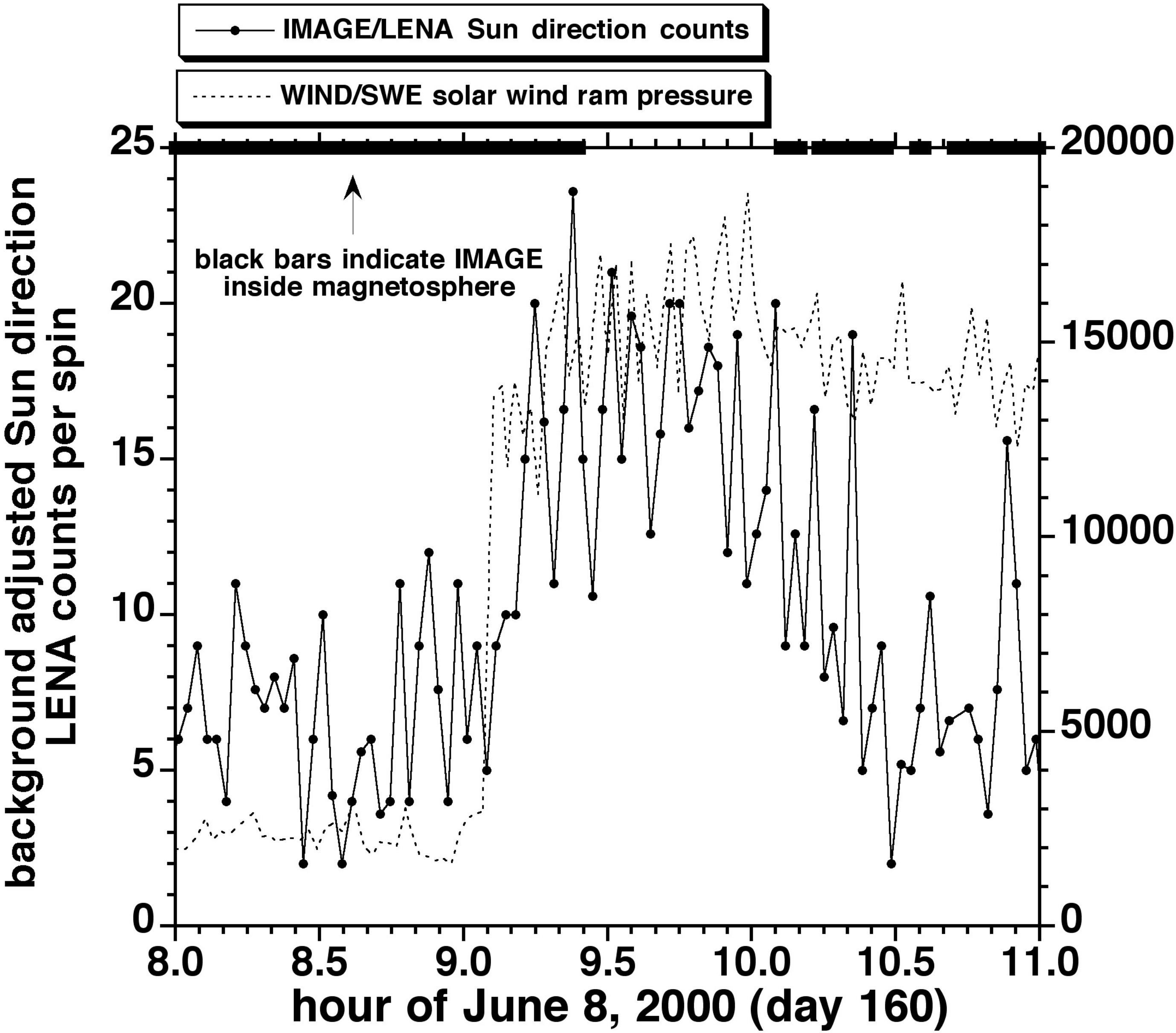

IMAGE/LENA
Spin Angle
270
180
90
0
-90
08:00
08:30
09:00
09:30
10:00
10:30
11:00
June 8, 2000
log count Rate [Hz]
1
0

figure 1



SOHO/SEM
10^{11}
10^{10}
EUV flux (photons/cm^2/s)
event
24-34 nm
0.1-50 nm
June 7
June 8
158.5
159.0
159.5
160.0
160.5
day of year 2000

figure 2



IMAGE/LENA Sun direction counts
WIND/SWE solar wind ram pressure
black bars indicate IMAGE inside magnetosphere
background adjusted Sun direction LENA counts per spin
solar wind ram press (pPa)
hour of June 8, 2000 (day 160)
25
20
15
10
5
0
20000
15000
10000
5000
0
8.0
8.5
9.0
9.5
10.0
10.5
11.0

figure 3

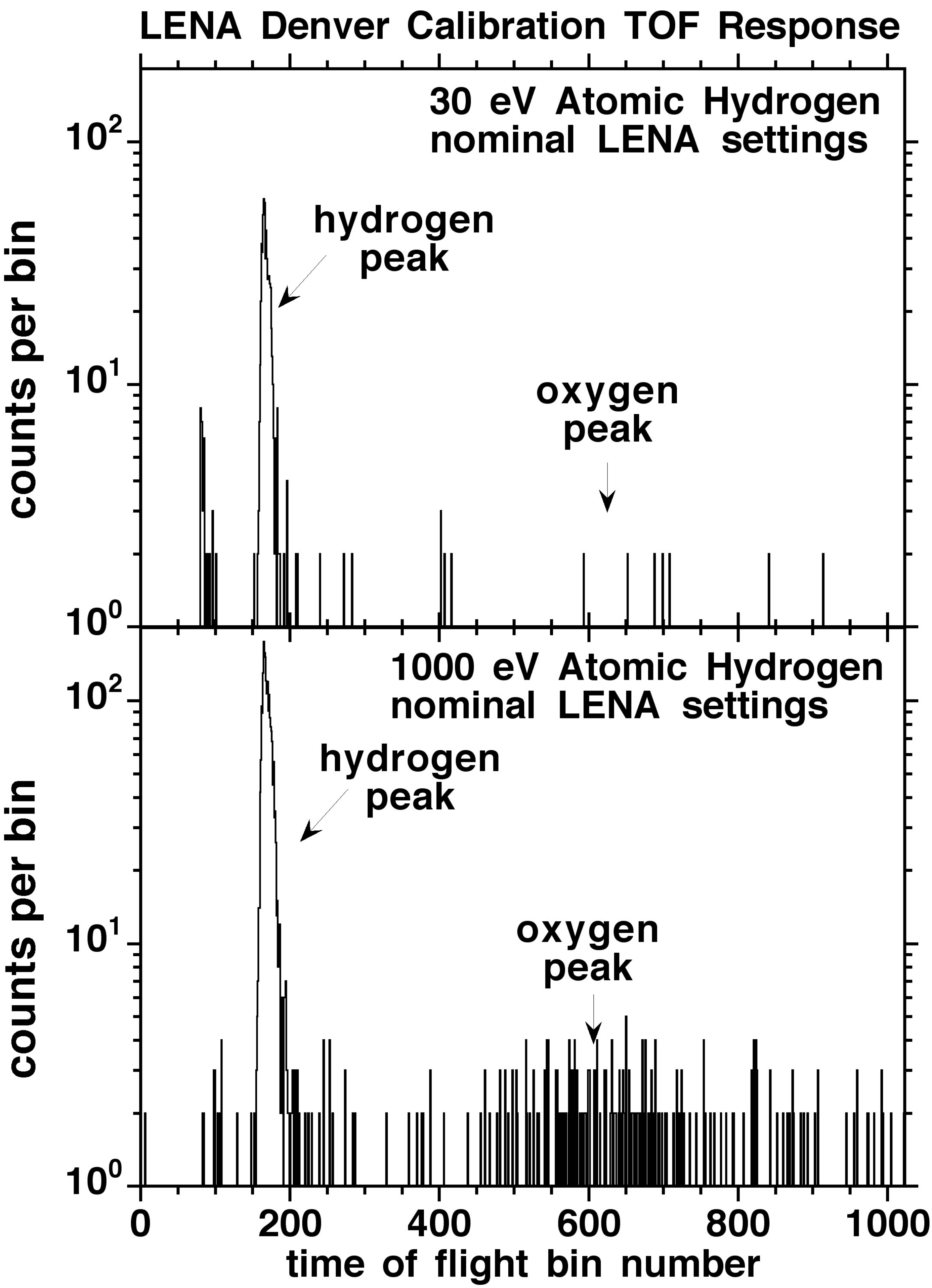

LENA Denver Calibration TOF Response
30 eV Atomic Hydrogen
nominal LENA settings
hydrogen peak
oxygen peak
1000 eV Atomic Hydrogen
nominal LENA settings
hydrogen peak
oxygen peak
counts per bin
counts per bin
10^2
10^1
10^0
10^2
10^1
10^0
0
200
400
600
800
1000
time of flight bin number

figure 4

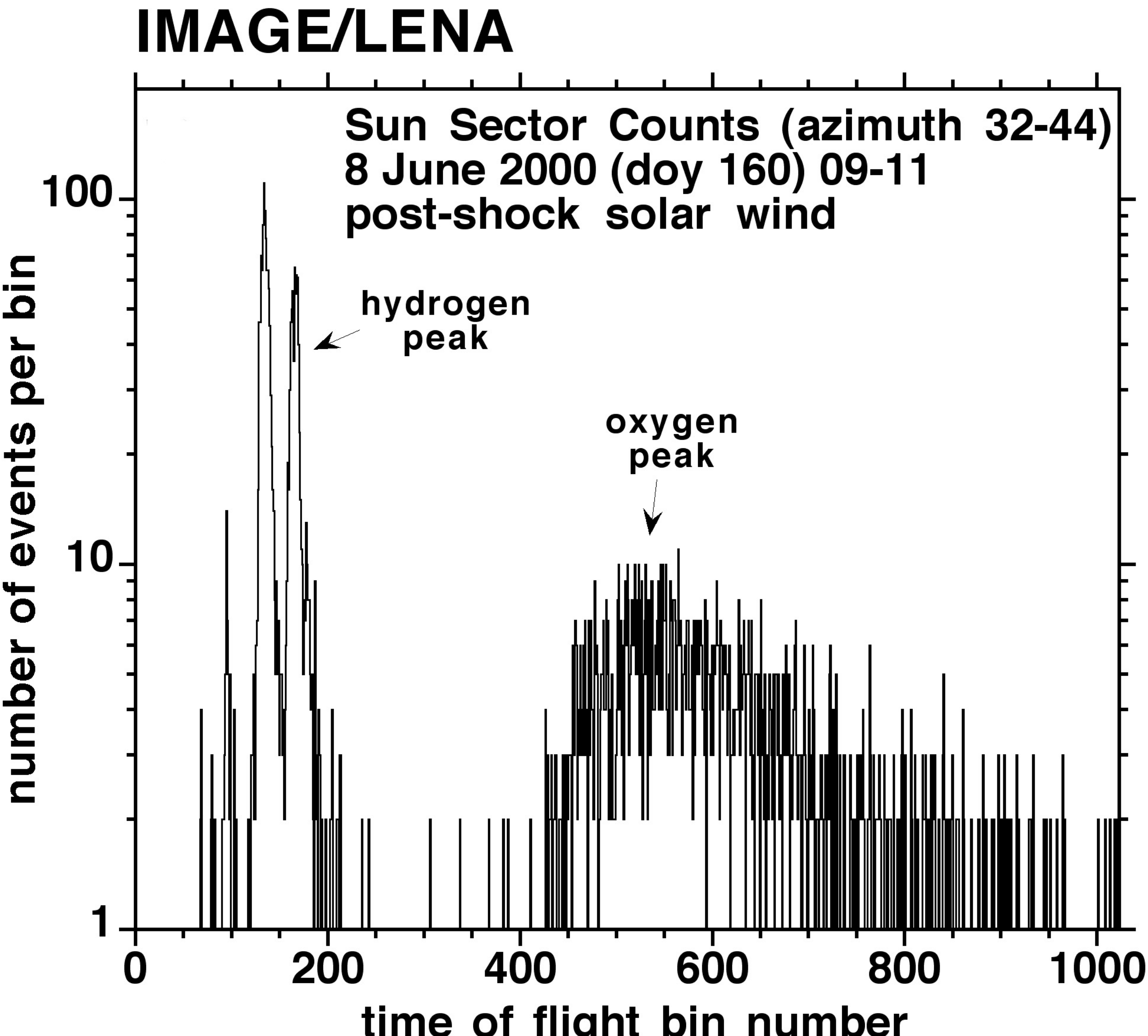
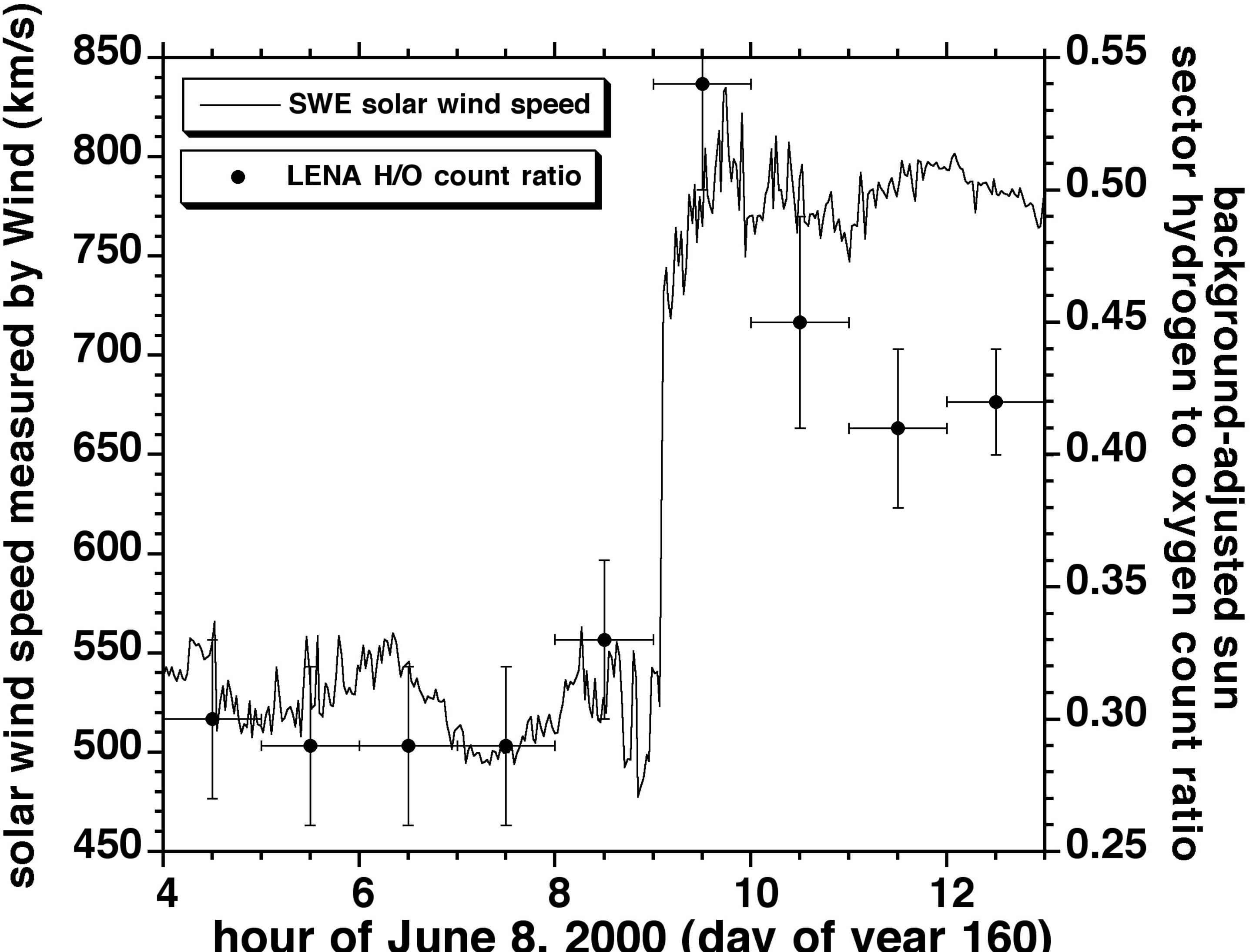

IMAGE/LENA
Sun Sector Counts (azimuth 32-44)
8 June 2000 (doy 160) 09-11
post-shock solar wind
hydrogen peak
oxygen peak
number of events per bin
100
10
1
0
200
400
600
800
1000
time of flight bin number

figure 5



SWE solar wind speed
LENA H/O count ratio
solar wind speed measured by Wind (km/s)
850
800
750
700
650
600
550
500
450
background-adjusted sun sector hydrogen to oxygen count ratio
0.55
0.50
0.45
0.40
0.35
0.30
0.25
4
6
8
10
12
hour of June 8, 2000 (day of year 160)

figure 6